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Effect of Curing in a High Temperature Environment on Compressive Strength of Concrete Incorporating Different Complementary Cementitious Materials

by R. Rivera-Villarreal and J. M. Rivera-Torres

Synopsis: This paper provides results of different types of curing in hot weather environment on the compressive strength of concrete made with portland cement and complementary cementitious materials (CCM) such as natural pozzolans, fly ash (FA), granulated blast furnace slag (GBFS), and silica fume (SF). In all concrete mixtures, a superplasticizing admixture (SPA) was used.

Nine series of concrete mixture were made. In seven of them (1, 2, 3, 4, 5, 6 and 9) the normal portland cement (NPC) content was 200 kg/m^3 and in two of them (7 and 8) the same amount of cement was used but it was a portland-natural pozzolan cement (PNPC). The CCM varies from 9.9 to 60.6% of the total cementitious material. The W/C in all series was 0.70 when using NPC or PNPC. The W/C+CM varied from 0.28 to 0.63. In all series the same amount of 1260 kg/m^3 of coarse aggregate was used.

Five different ways of curing were used. One was the initial and final ASTM curing at 23°C up till the age of testing as reference, and four different ways of curing in hot weather environment at 37°C for the first 24h were used. These final curings were: A) ASTM; F) three day and G) seven-day water spray for 15 minutes every 2h; and (E) covered by two layers of membrane.

Adequate compressive strength development (CSD) can be obtained using CCM but very good curing is necessary. Generally, by casting specimens at 37°C and put them under ASTM curing next day at 23±2°C (A), the strength at 28 days was lowered by about 8% and at six months by about 8% lower than these casting at 23°C.

Membrane curing was less effective at later ages mainly when fly ash was used. There exist an optimum amount of fly ash to obtain maximum compressive strength at later ages.

Keywords: compressive strength; final curing; fly ash; high temperature; membrane; portland cement; pozzolans; silica fume; slag; superplasticizer

R. Rivera-Villarreal, Professor Emeritus in Civil Engineering at the Universidad Autónoma de Nuevo León (UANL), is ACI and RILEM Fellow and ACI Honorary Member, member of ACI Committees 120, 236, E 701, E 802, E 803. Researcher Level II National Program of Researchers. President of the Education Activities Committee and Advisor of the FIC-UANL ACI Student Chapter of the North East México Chapter. Chairman of the RILEM 158 AHC. Chief of Concrete Technology Department at the Civil Engineering Institute, Titular Professor of Concrete Technology and Laboratory at the School of Civil Engineering (FIC), UANL, Monterrey.

J. Rivera-Torres: Civil Engineer, Research Assistant, and Concrete Technology Laboratory Professor Assistant at the School of Civil Engineering at UANL, Monterrey. Accredited as examiner for ACI Certification of Field Technicians on Reinforced Concrete Structures.

INTRODUCTION

In September 2000, the Strategic Development Council of the U. S. concrete industry launched an interesting project for the future of the concrete industry; a Unified Vision for concrete technology and its social impact 30 years from now; it was called Vision 2030. Predicting that by the year 2030 the industry will make processing improvements throughout the life cycle of concrete, and that as a logic consequence of this, concrete will become the most efficient and cost-effective material for construction.

This Vision expects that aggregates quarries, cement manufacturing, ready-mixed and concrete product plants will be viewed as assets to their neighboring communities. And one of the main strides is to use a variety of by-products from other industries as well as recycled concrete as a constituent materials in new concrete production [1].

Environmental issues will have a leading role in the sustainable development of the cement and concrete industry in the 21st century. Increased emission of greenhouse gases to the atmosphere is no longer environmentally and socially acceptable for overall sustainable development. The primary greenhouse gas emissions are carbon dioxide (CO_2) emissions. As the manufacture of portland cement contributes significantly to the CO_2 emissions, it is imperative either to develop new environmentally friendly cement manufacturing technologies, which should be economically acceptable; or to find substitute materials to replace a major part of the portland cement used in the concrete industry. The use of large volumes of fly ash and other CCM in the construction industry contribute in reducing these emissions [2]. These materials are cheaper than portland cement; therefore, the benefits of using these materials are environmental as well as economical.

Water permeability of concrete cover is related to durability and is usually associated with good concrete mixture design and workmanship. Microstructure of NPC is remarkably influenced when it is blended with a very fine ground CCM. The CCM densify the microstructure of hydrated cements, decreasing porosity that influences the overall properties of the resulting material. Good concrete practice should include adequate compaction and suitable curing. Early and long moist curing has been identified as an important requirement for durable concrete [3]. However, such curing requirement is often ignored in the actual construction process mainly when producing high strength concrete (HSC). Various references to the importance of concrete curing in hot weather environments can be found in [4,5,6, & 7].

The appropriate use of a suitable CCM and a HRWRA is expected to produce workable, strong and durable concrete. The pozzolanic CCM will react with calcium hydroxide that is the weakest compound formed and is liberated after the hydration of cement, which ends up in C-S-H hardened compounds and in a refined micro pore structure in concrete. The combined effect of pozzolanic reaction and the very fine particle size of CCM was expected to improve the strength as well as the water permeability of concrete.

Capillary voids and micro cracks, which are generally connected or interlinked, have a great influence on concrete permeability. The amount and size as well as connectivity of capillary voids depend on the W/C and its hydration [8].

The permeability of cement paste has also been related to concrete durability. A great deal of work has been done measuring and predicting permeability of cement paste. One aspect between permeability and pore structure of hardened cement paste was presented by Nyame, et al [9].

Many researches are going on using ternary cementitious materials to get sustainability of concrete materials with fly ash and slag as partial cement replacement materials, looking for good strength development in high strength and non-permeable concrete. One of these studies made with ash of Timber Industrial (TI) included concrete subjected to different curing conditions [10], they obtained good results for concrete grade 80 MPa in the pre-cast concrete industries. Autoclaved curing enhanced the potential of developing early strength.

Several techniques have been applied to study the pore structure of cement paste, such as the measurements of surface area and porosity by using mercury intrusion porosimetry (MIP), Brunaver-Emmett-Teller (BET) analysis, and surface electron microscopy (SEM).

This study is an attempt to explore the possibility of producing durable and sustainable concrete in hot weather with minimum moist curing, and minimum amount of portland cement.

Materials

Two types of cement were used according the Mexican Standard NMX C414-1999; CPO 30R similar to ASTM C 150 type I portland cement and CPP 30R similar to ASTM C 595-98 blended hydraulic cement type P, but with a higher 28-day-strength-minimum of 30 MPa. The CCM used were: natural pozzolan, FA, GBFS, and condensed SF. The chemical analysis of all cementitious materials used is shown in Table 1 and physical properties in Table 2. The FA used meets ASTM class F requirements, except for the fineness, which is somewhat coarser, passing 45 μm 58% instead of 66% by ASTM.

The aggregates used were crushed limestone from Monterrey, N. L., Mexico area. The fine aggregate had a dry relative density of 2.68 and SSD absorption of 1.5%. The coarse aggregate had a dry relative density of 2.66 and SSD absorption of 0.7% and a 20.0 mm nominal maximum size.

Since in this study the concrete consistency is a factor, it is of great importance that the values measured through the consistency test should not be affected by aggregate grading variations. To avoid this problem and to maintain a uniform grading for each mixture, the fine and coarse aggregate were separated into different size fractions, which were then recombined in the required amount for each batch to provide the selected specific grading. The mean fine and coarse aggregate grading is shown in Table 3.

A sulfonated formaldehyde naphthalene concentrate superplasticizer admixture (SPA) with 1.12 density, was used in all nine series.

Mixture proportions

Nine concrete series (1 to 9) were made using different amounts of CCM as shown in Table 4. In seven of them (1 to 6, and 9) 200 kg/m^3 of NPC was used; and in Series 7 and 8 the same amount of cement was used, but it was PNPC. In all nine series the same amount of water was used to have W/C = 0.70. In Table 4 the amount and percentages of each CCM used are shown. In reference Series 1 only NPC was used; in Series 7 only NPPC (22 kg/m^3) was used. In all other seven mixtures using different amounts of CCM, the same amount of SF was used. This amount corresponds to 9.9% of NPC or NPPC.

One of the reasons why all the mixtures have the same amount of water (140 kg/m^3) and 200 kg/m^3 of NPC or NPPC with a W/C= 0.70, was to have the same amount of calcium hydroxide produced during cement hydration. The

W/C+CC varies from 0.70 to 0.28 and the yield of cementitious materials from 200 to 507 kg/m^3.

In all series, the amount of coarse aggregate was 1260 kg/m^3. To maintain the same amount of cement and water when using CCM, it was necessary to adjust the absolute volume of CCM deducting it from the corresponding amount of fine aggregate which in the reference series (without CCM or SPA) was 891 kg/m^3.

SPA was used in all nine series, the total amount added was adjusted to give a final slump of 220 ± 20 mm. The mixture proportions are shown in Table 5.

Mixing and Casting

An Elrich concrete mixing machine 45L capacity was used, the drum rotating to 30 rpm and the paddles in countercurrent 450 rpm. The mixing procedure for reference concrete series 1 was as follows: To ensure the correct final proportions in the test batch, just prior to mixing the first batch, the mixer was buttered by mixing a batch proportioned to simulate closely the test batch. The mortar adhering to the mixer after discharging is intended to compensate for loss of mortar from the test batch. The dry aggregates and a part of the mixing water were put into the drum and the machine was started for a half of minute to saturate the aggregate; then, without stopping the machine the cementitious materials (200 kg/m^3 of portland cement) were added, including the rest of the water needed to have 0.70 W/C. When all the materials were into the drum, the mixing continued for an additional minute. The machine was stopped for one minute, after that resting period, the mixing continued for one more minute. The machine was stopped and immediately the slump test was performed to measure the initial slump. After that, SPA was added to attain a slump of 220±20 mm, mixing for one more minutes.

The mixing procedure for all other series was similar except that when the remaining water was added, the fourth part of the SPA admixture was included to facilitate the mixing. After the resting period of one minute, the remaining SPA was added without stopping the machine and the mixing continued for one more minute.

Initial slump for the reference mixture was 40-50 mm, and the final slump was 220 ± 20 mm after adding SPA. Except for the reference mixture made at 23±2°C, all mixtures were made at 37°C ± 1. Specimens were casted in molds of 100 mm in diameter and 200 mm in height, three for each compressive strength test at the specified ages of 3, 14, 28 days, 3, 6 months and one year. However, only age 6 months results will be provided in this paper. Additional specimens were made to measure porosity and permeability up to 6 months, but the results are not included in this paper.

Specimens were stored under five different curing conditions up to the age of testing. Daily information on ambient temperature, humidity, and evaporation was recorded; and the average high and minimum monthly values were determined as shown on Fig. 1.

Fresh Concrete Properties

All concrete series were casted at two different nominal concrete temperatures, 23°C and 37°C, as shown in Table 6, along with the determined air content, laboratory temperature, concrete temperature, and slump.

The dosage of SPA was adjusted in all the mixtures to obtain a final slump of 220 ± 20 mm, as shown in Tables 5 and 7.

Fresh Concrete

In Table 7 we can see that when the concrete temperature increases, so does the dosage of SPA increases as percentage of the Cementitious Material used. A very high increment is registered when no CCM were used, such mixtures are reference series 1 and 7. A higher increment is observed for reference Series 7 in which PNCP was used, this cement has natural pozzolans intergrinded. Portland Cement is the coarser particle size of cementitious materials, but to compensate the absolute volume when CCM is added, as already mentioned in Mixture Proportions, CCM added is finer than the finer aggregate that is substituting. As it can be seen in Table 5 where the % of SPA is about the same to have the same final slump. There is a possibility that the efficiency of a naphthalene based SPA is increased considerably when very fine cementitious materials are used instead of very fine aggregates. Albeit, more research is needed to confirm this possibility.

When the laboratory temperature was maintained at 23° C ± 2, the concrete temperature rose up from 30° to 33.5°C; an average increment of 7.4° C; when the laboratory temperature was maintained at 37.5°C ± 0.5, the concrete temperature rose up from 38° to 40.5°C; an average increment of 2°C.

Curing

Five different ways of curing were used, it is important to define that we call initial curing those made the first 24 h and final curing after 24 h.

For the reference concrete (Series 1), ASTM C31M-96 curing (R) was used for initial and final curing.

For the rest of the concrete the initial curing was under a temperature of 37°C ± 1 and humidity of 60% ± 10, which were the same temperature and humidity used when casting the concrete specimens, simulating a hot weather environment.

The final curing types (A, F, G, E) were as follows (see Table below):

TYPE OF CURING	INITIAL CURING		FINAL CURING	
R	Dry	23°C	Std ASTM curing room	23°C
A	Dry	37°C	Std ASTM curing 100% RH	23°C
F	Dry	37°C	3 day water spray every 2h	Ambient under shade
G	Dry	37°C	7 day water spray every 2h	Ambient under shade
E	Dry	37°C	Membrane	Ambient under shade

Curing A Standard ASTM (23 and 100% RH after 24 h)

Curing F 3 days spraying specimens with water 15 minutes every 2 h in ambient temperature under shade and no more water in same ambient till the time of test.

Curing G 7 days spraying specimens with water 15 min every 2 h in ambient temperature under shade till the time of test.

Curing E 2 layers of a membrane compound applied to specimens (200 mL/m^2 per layer) and then ambient temperature under shade till the time of testing. Carefulness was in applying the first layer of membrane to the surface when concrete be saturated but surface dry. To be sure not to lose any amount of water, prior to applying the membrane the specimens were soaked in water and surface dried.

Environmental Conditions

The environmental conditions of daily minimum, mean and highest temperatures, the daily minimum, mean and highest relative humidity (RH) and the daily minimum, mean and highest evaporation were recorded on site of curing. In Fig. 1 average monthly values are shown.

During the six months of environmental curing, May through November the highest temperature varies from 28.5°C to 37.5°C. The minimum relative humidity varies from 32.8% to 53.8% and the maximum evaporation varies from 0.24 L/m^2/h to 0.46 L/m^2/h.

Compressive Strength

Compressive strength was determined according to ASTM C-39-96 with the following modifications for those specimens under curing F, G and E. Prior to testing of specimens they were soaked in water for two hours trying to have saturated all the specimens at time of test. In the case where membrane was used, it was removed by scraping it prior to putting the specimens in water.

In Table 7 compressive strength results for all series are shown, as well as type of curing.

RESULTS AND DISCUSSION

In all series, the minimum compressive strength was obtained when using the type F curing which was an intermittent spray with water 15 min. every two hours curing for three days, and then left under shadow up to the age of testing (Fig. 3 thru 11).

In all series, Fig. 3 to 11, the curing type G that was an intermittent spray with water 15 min. curing every two hours for seven days, the compressive strength increased very little compared to type F curing for higher W/C+CM; for lower W/C+CM the difference was about 10%.

In all series, Fig. 3 to 11, the compressive strength with Type E membrane curing was similar to type G curing in that little difference in strength was observed. The membrane curing type E prevented any loss of humidity after applying the first membrane layer.

In series 4, 5, and 6, fly ash was used and the compressive strength data are shown in Fig. 6, 7, and 8. There was a high difference in the way of curing in those having few water as curing F, G and E, the compressive strength is lower than those having more water available as type curing R and A at 28 days and strength increase of about 15% is observed and for later ages as 90 or 180 days, the strength increase is higher about 35%. This means that fly ash concrete needs good water curing for a long time to increase strength development.

The compressive strength development of the nine series of concrete mixtures for each five types of curing is shown in Figures 12, 13, 14, 15 and 16.

In all series, the curing type R, in which the standard ASTM curing were used all the time attained maximum compressive strength at ages 28 days and higher, except Series 6 in which was used the maximum CCM of 307 kg/m^3 as shown in Fig. 8. In this case, casting was at 37°C and being for 24h at this temperature following with curing soaked in water curing at 23°C (Type A curing).

Series 3 having less than 50% of cementitious materials than Series 5 has higher early strength and about the same late strength (Fig. 17 to 21). The difference is that Series 3 has 27.7% GBFS and series 5 has 53.0% fly ash. Both series have same amount of portland cement SF and water. The effectiveness of GBFS was better than fly ash used.

Series 4 and 5 (see Fig. 6 and 7) have the same amount of portland cement, SF, water and very little amount of SPA. The main difference is that the amount of fly ash in Series 4 had 200 kg/m^2 and Series 5 had 250 kg/cm^3, a difference of 50 kg/cm^3 of more fly ash, but the compressive strength of Series 4 has about the same strength. This means that there exists an optimum amount of fly ash for maximum strength.

In series 2 to 6 the same amount of PC (200 kg/m^3), the same amount of water (140 kg/m^3), the same amount of SF (22 kg/m^3) and same slump (220 ± 20 mm) were maintained. The superplasticizer dosage varied with ambient temperature from 1.22 to 1.35% of solids of total cementitious materials for 23°C and 1.30 to for 37°C. Series 2 and 6 have the same amount of PC and SF and same initial hot curing (37 °C) but different W/C+CM, Series 2, 0.63 abd Series 6, 0.28, the last one has quaternary cementitious materials in which we added furthermore FA and GBFS. For the same curing A, Series 2 (Fig. 4) the compressive strength at 6 months was 44.5 MPa and in Series 6 (Fig. 8) the compressive strength was 94.8 MPa, an increase of 213%.

The reference Series 1 (Fig. 3) with portland cement CPC 30R similar to ASTM type 1 and Series 7 (Fig. 9) with PNPC without any CCM but with SPA for reference R curing. The Series 7 with PNPC give more strength of 11.1% at 28 days and 22.1% at six months.

The Series 2 (Fig. 4) with portland cement and Series 8 (Fig. 10) with same amount of PNPC and same amount of SF and SPA have no difference for reference curing R in compressive strength at 28 days, but at six months Series 8 is higher 5.0%.

The Series 3 and Series 9 have same amount of portland cement and same amount of SF and using SPA. The only difference was that series 3 has 85 kg/m^3 of GBFS, and series 9 has 85 kg/m^3 of NP at 28 days series 9 with reference curing R had a 7.0% higher compressive strength and at six months 10.0%.

CONCLUSIONS

In hot weather environments usually the specimens are made and left at the site for the first 24 h. After that, they are cured under >95% humidity and 23 ± 2°C temperature, which is similar to curing type A. In this type of curing against type R curing, which is ASTM curing (casted at 23°C), under the conditions established in this study and for any amount of cementitious materials, the compressive strength at 28 days was lower for a mean value of 10.0% at later ages about the same 12.0%, except for Series 3 and 6, where GBFS was used, in Series 3 it was of only about 5.0% lower at 28 days and 13.0% at later ages, but in Series 6, besides using the same amount of GBFS, but a great amount of total cementitious material as about 60.0% by volume, which lowers W/C+CM to 0.28 at 28 days, practically is the same for both types of curing. For later ages as 180 days, the strength level was higher about 10.0% for curing A.

Two layers of good applied membrane were not as good as continuous water curing mainly when fly ash was used as in series 4, 5, and 6 when a 20% less compressive strength at 28 days and about 45.0% at six months of concrete casting at 37°C were obtained.

Intermittent water at 15.0 min for every 2h for 7 days is not enough to gain strength development as continued water curing. It will be similar to two layers of membrane.

Some GBFS, as used in this study, was more effective in developing compressive strength. Series 3 had an additional 85 kg/m^3 of GBFS and Series 5 had an additional 250 kg/m^3 of fly ash and other materials the same, even the higher amount of fly ash the compressive strength is around the same for any age and type of curing, with less amount of water as curing F, G, and E. For curing with water the Series 5 with fly ash have 12.0% higher at 28 days and about 27.0% at six months.

044-V

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REFERENCES

1. Vision 2030: A Vision for the U.S. Concrete Industry. Concrete International, Farmington Hills, Mi, Vol. 23 No. 3 March 2001 pp. 25-34.
2. Malhotra V. M. “Making Concrete “Greener” with fly ash” Concrete International Vol. 21, No. 5 May 1999, Farmington Hills, Mi pp. 61-66.
3. Mansur, M.A., Wee, T.H. & Chin, M.S. “Some Engineering Properties of Locally Produced High Strength Concrete.” Proc. 19th Conference on Our World in Concrete & Structures. Singapore 1994, pp. 97-106.
4. Mehta, P.K., Monteiro, P., “Concrete, Structure Properties and Materials”, Prentice Hall 2nd Edition, Englewood Cliffs, NJ, 1993.